EAARL: A LIDAR FOR MAPPING SHALLOW CORAL REEFS AND OTHER COASTAL ENVIRONMENTS*

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Abstract

The EAARL (Experimental Advanced Airborne Research Lidar) is a new airborne lidar that provides unprecedented capabilities to survey coral reefs, nearshore benthic habitats, coastal vegetation, and sandy beaches. The EAARL sensor suite includes a raster−scanning−water penetrating full−waveform adaptive lidar, a down−looking color digital camera, a hyperspectral scanner[1], and an array of precision kinematic GPS receivers which provide for sub−meter geo−referencing of each laser and hyper−spectral sample.

EAARL has the unique real−time capability to detect, capture, and automatically adapt to each laser return backscatter over a large signal dynamic range and keyed to considerable variations in vertical complexity of the surface target. These features enable automatic adaptive acquisition of dramatically different surface types in a single EAARL overflight. This makes EAARL uniquely well suited for mapping applications such as coral reefs, bright sandy beaches, coastal vegetation, and trees where extreme variations in the laser backscatter complexity and signal strength are caused by different physical and optical characteristics.

1. Introduction

Airborne lidar for bathymetric and topographic mapping has undergone extensive development and refinement since the early 1970's. Much of the advancement of lidar has directly tracked advances in high speed digital and analog electronics. Several order of magnitude advancements in computer technology have greatly increased computer memory and storage capacity, access and processing speed, while simultaneously and dramatically reducing cost. These advances coupled with the implementation of GPS and kinematic carrier−phase GPS position measurement in the 1980's have resulted in low cost airborne lidars that are of great value within numerous natural science applications.

Bathymetric and topographic lidars rely on making an accurate measurement of the round trip time−of−flight of a laser pulse from the lidar system to the surface or surfaces.

Traditional bathymetric systems have been generally designed and optimized to measure water depth by a factor of 2−5 beyond the point where a Secchi disk disappears from view due to either diffusion, absorption or a combination thereof (Guenther 2000). High laser power and a large receiver field−of−view (FOV) are both desired characteristics for deep diffuse waters. The prevailing laser technology can generally deliver either high pulse power or high pulse repetition, but not both at the same time. A laser bathymetry system designer must therefore decide which is more important in addressing his design goal. Most systems use a

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combination of several milli–joules/pulse and PRF rates between 200 and 1000 HZ.

Lasers used for bathymetry must be blue/green in color to afford water penetration, but this is also the spectral region at which the human eye is most sensitive. In order make the system meet ANSI eye safety standards, the laser beam is frequently spread causing the spot on the surface to be several meters in diameter and the laser energy density reduced to the point where it can be safely viewed by people on the surface. The net result of the stated design parameters and goals will yield a system with optimal depth measuring capability in deeper diffuse water. However, this basic design is less than optimum for high spatial density and resolution in clear shallow (< 10m) water, especially in comparison to state–of–the–art terrestrial mapping lidar.

For optimum depth recovery in diffuse water, it is generally accepted that the diameter on the water's surface viewed by the lidar should be on the order of ½ the expected depth. Accordingly, if the maximum nominal operating depth is 40 meters, the FOV diameter at the surface would need to be 20 meters which corresponds to 33 milliradians.

Most bathymetric lidars measure water depth by measuring the time–of–flight of a laser pulse between the surface of the water and the bottom. Corrections are typically made to remove waves and tidal effects and this produces a hydrographic map describing water depth referenced to mean low water. Another important effect that must be accounted for is the ambiguity in the origin of the water surface backscatter and subsequently, the range to the water surface. The backscatter from the water surface is convolved with the backscatter from the initial water column such that it can be difficult to determine exactly where the atmosphere ends and water surface begins (Guenther, 1996). Various techniques have been employed to mitigate this problem (Guenther, 1996).

The traditional airborne topographic mapping lidar employes a much higher pulse repetition frequency (PRF) (2–40 kHz) than a typical bathymetry system. Nearly all operate in the near–infrared region of the spectrum. Nominal lasers include pulsed laser diodes operating at 940nm and pulsed diode–pumped Infrared ND–YAG lasers operating at their fundamental wavelength of 1064nm. Most systems use high speed electronics to measure the time interval between when a laser pulse leaves the lidar and when the backscatter from the surface returns to the lidar. The topographic surface reflection may be complex and consist of multiple reflections from surface features which have vertical extent such as trees and other vegetation. Over a forest, for example, a return may originate either from the top of the canopy, the understory, or the underlying terrain.

Table 1. Basic system specifications for the EAARL system.

EAARL System Specifications	
Total system weight	250 lbs
Maximum Electrical power requirements	28 Vdc @ 25 amps
Nominal surveying altitude (AGL)	300 m
Nominal surveying speed	97 Knots (50 m/sec)
Raster scan rate	25/second
Laser samples per raster	120
Swath width @ 300 m altitude	240 m
Sample spacing	2x2m swath center 2x4m swath edges.
Nominal Linear area covered per hour (300m altitude, 50m/sec)	43 Sq. km/hour
Nominal power required	400 Watts
Illuminated laser spot diameter on the surface @ 300 m altitude	15 cm
Nominal ranging accuracy	< 3 cm air water TBD
Nominal horizontal sample positioning accuracy	Within 1 meter
Digitizer sample interval	1–ns (14.9cm in air) (11.3cm in water)
Minimum water depth	30 cm
Maximum measurable water depth	25 m

Many topographic lidars systems measure only the time interval to the "first return" and ignore any subsequent backscatter from the target. Some systems capture the time to the leading edge of the backscatter and the time to the last leading edge within the backscatter. Such a "First and Last" system has a much higher likelihood of detecting the bald earth under a forest or vegetation canopy than does a "first return" system. Still other systems use a "multi–stop time interval unit" to capture the time of the leading edge of the backscatter and the time interval to each subsequent edge within the back–scatter.

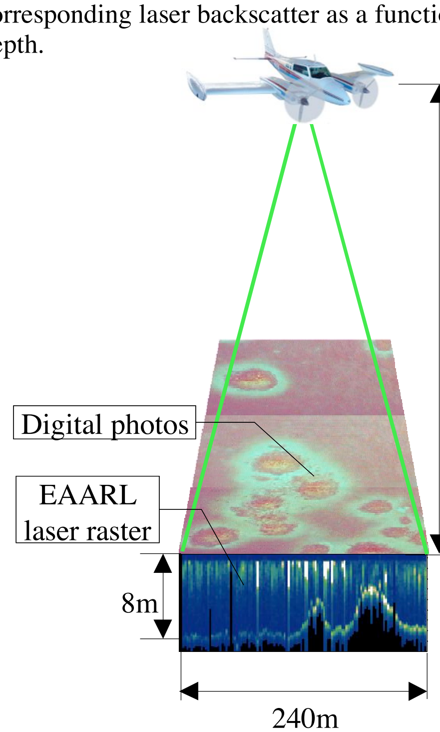
2. EAARL Description

The EAARL system builds on knowledge and experience gained through the development and refinement of the Airborne Oceanographic Lidar (AOL), the Airborne Topographic Mapper (ATM), and the Scanning Radar Altimeter (SRA). A "full waveform digitizing" concept was first used on the AOL in 1996 (Wright, 2001), and again in 1998 on the SRA (Wright, 1999). The EAARL system described here combines shallow bathymetric and topographic mapping capabilities and features in a single system which can be deployed to undertake cross–environment surveys of shallow submerged topography, sub–aerial topography, and vegetation covered topography in a single flight.

Table 1 outlines the basic system specifications for the EAARL system. EAARL differs from traditional bathymetric lidars in several significant ways. In the bathymetric case, EAARL emphasizes measurement of the bottom topography as opposed to measuring the overlying water depth. EAARL also measures bottom topography relative to the precise GPS determined aircraft position instead of relative to mean low water. The total range vector from the aircraft to the bottom is thereby conserved. That portion of the range vector in air is adjusted for the speed of light in air, and that portion determined to be submerged is adjusted for the speed of light in water. In this way, the impact of any errors introduced by uncertainty in determining the exact location of the surface of the water are minimized when computing the elevation of the submerged topography.

In ocean optics terminology, the EAARL optical operation is best described as being in the narrow beam attenuation mode as opposed to the broad beam diffuse attenuation mode. It illuminates, with eye–safe energy densities, a small spot (15 cm diameter) on the surface. The small surface spot minimizes geometric pulse stretching at the surface and also minimizes the reflecting surface area The reduced EAARL receiver footprint aids in rejecting ambient light and also reject laser light which has been widely scattered by the water column or surface characteristics. The smaller receiver FOV results in much less broadening of the surface and bottom return pulses but also results in a more rapid decay of the bottom return signal. Most of the multiply scattered photons which are detected in a large FOV system have taken much longer paths back to the lidar receiver and thus contain the wrong time–of–flight information and will not make a desirable contribution to the true bottom signal. Figure 1 shows a schematic of a representative EAARL flight segment. The photo portion is from the co–registered digital camera and the lidar data is underwater backscatter as a function of depth in the vertical axis and laser scan angle in the horizontal axis. The broad green and yellow portions of the backscatter just below the surface represent backscatter from entrained turbidity in the water column. The bright white lines indicate laser returns which contained a significant surface Fresnel reflection. Two small patch reefs are clearly shown on the right side of the raster and significant variations in the

Figure 1. An EAARL digital photo and the corresponding laser backscatter as a function of depth.



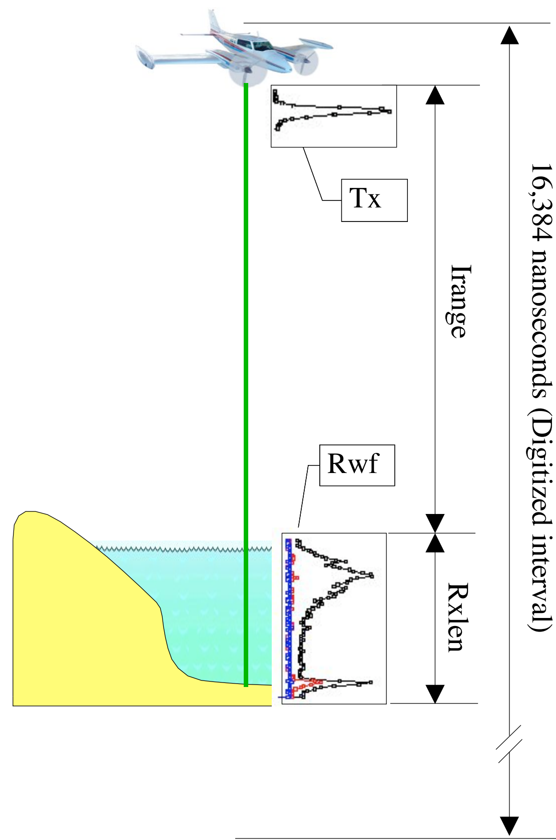
turbidity can be observed in the water overlying the right most reef as compared to the turbidity in the rest of the raster.

EAARL uses a very low power eye safe laser pulse in comparison to traditional bathymetric lidar systems, EAARL uses a much higher PRF (pulse repetition frequency) and significantly less laser energy per pulse (approximately 1/70th) than do most bathymetric lidars. The EAARL pulse energy is only 70 micro–joules/pulse as compared to 5000 micro–joules/pulse for other state–of–the–art bathymetric lidars. The average PRF of the EAARL system is 3000 Hertz while the peak PRF approaches 5,000 Hertz through the center of the swath. Based upon recent test flights over typical Caribbean coral reef environments, EAARL has demonstrated penetration to greater than 25 meters, and can routinely map coral reefs ranging in depth from 0.5 to 15 meters below the water's surface.

The system uses a "digitizer only" design which eliminates all hardware based high speed front–end electronics, start/stop detectors, time–interval–units, range gates, etc. typically found in lidar systems. The EAARL system instead uses an array of four high speed waveform digitizers connected to an array of four sub–nanosecond photo–detectors. Real–time software is used to implement the system functions normally done in hardware.

Each photodetector receives a fraction of the returning laser backscattered photons. The most sensitive channel receives 90% of the photons, the least sensitive receives 0.9%, and the middle channel receives 9%. A fourth channel is available for either water Raman or 1064nm infrared backscatter depending on the application. All four channels are digitized synchronously with digitization beginning a few nanoseconds before the laser is triggered, and ending over 16,000 nanoseconds later. A small portion of the laser is sampled by fiber optic and injected in front of one of the photo–detectors to capture the actual shape, timing, and amplitude of the laser pulse shortly after it is generated. A total of 65,536 total samples are digitized for every laser pulse, resulting in over 150 million digital measurements being taken every second. The resulting waveforms are partially analyzed in real–time to locate the key features such as the digitized transmit pulse, the first return, and the last return. Once the key features are located, they are recorded on hard drives. The real–time waveform processor automatically adapts to each laser return waveform and retains only the relevant portions of the waveform for recording. Thus, the storage space required for returns from tall trees or deep water is more than the storage requirement for beach or shallow water backscatter. Figure 2 depicts how the EAARL waveform data are captured.

Figure 2. Schematic of EAARL adaptive laser returns from a bathymetric target, indicating transmit (Tx), received waveform (Rwf), receiver waveform length (Rxlen), integer range to first surface (Irange), total interval digitized per pulse (Digitized interval).



2.1 Optics

The EAARL laser transmitter consists of a Continuum EPO–5000 doubled YAG laser producing up to 5000, short 1.3 nanosecond duration, 70 micro–joule, 532nm pulses each second. The laser also concurrently generates a three nanosecond 1064nm pulse which can be used to double EAARL's sample density for non–submerged topographic targets. Although the EAARL transmitter can operate up to 5 kHz, its pulse−repetition−frequency (PRF) is computer controlled and varied to produce nearly equal cross−track sample spacing thus equalizing the sample density within the EAARL swath.

The EAARL receiver optics consists of 1) a 15 cm diameter enhanced aluminum Newtonian telescope, 2) a computer driven raster scanning mirror oscillating at 12.5 Hz producing 25 raster scans each second, and 3) an array of sub−nanosecond photodetectors each sampling a specific dynamic range fraction of the backscattered laser energy. The computer driven scan mirror position is measured by a precision high speed shaft angle encoder which provides resolution of 0.045 degrees.

2.2 Data System

The EAARL data−system consists of an array of high speed RISC micro−controllers which "micro manage" the nanosecond to nanosecond operation of the lidar system and provide all timing and synchronization between the laser, the array of digitizers, and the host Linux based data acquisition computer where the EAARL data are ultimately processed in real−time and stored on removable 100 Gigabyte hard drives. The RISC micro−controllers reside on a special NASA developed interface card attached as a standard PC adaptor card to the Linux data system computer. The waveform digitizers are also attached to the same Linux data system computer.

Precision GPS synchronized time−of−day is developed as each laser pulse is carefully time−tagged by one of the RISC micro−controllers and then passed to the Linux data system.

2.3 Supporting Data

2.3.1 GPS and Tans Vector

In addition to the slant−range measurements made by the laser, accurate geolocation of EAARL data requires precise knowledge of the time−of−day, the aircraft attitude, heading, the exact geographic location in latitude, longitude, and altitude above the WGS−84 ellipsoid. Geolocation also requires the location and orientation of the EAARL mirror control point relative to the EAARL primary GPS antenna. The precision attitude (pitch, roll, heading) is acquired from a Trimble TANS−Vector GPS based attitude system 10 times per second. The exact geographic location of the primary EAARL GPS antenna is measured kinematically relative to a fixed GPS antenna back at the departure airport by two onboard Ashtech Euro−card GPS receivers twice per second. The TANS−Vector unit and each Ashtech receiver is serviced by a dedicated Linux based PC−104 data−system. Each PC−104 system operates independently to archive its respective data to onboard 6.4 Gigibyte hard−drives.

2.3.2 Digital Camera

One of the PC−104 systems also archives digital photographs which are taken each second throughtout the mission. The onboard PC−104 disk drive can hold up to 71 hours of digital camera data. The digital camera is a networked color camera co−registered with the EAARL optical system. It has approximately the same total field of view (45 degrees) as the EAARL scan width. By using this camera, we eliminate the need for a video recorder and video tapes. An additional advantage is that no VCR is required for playback, and the photo record of the flight can remain with the rest of the data set on the same storage devices. We have written image playback software which has proven to be much more useful than comparable video because we can easily synchronize the images with the lidar data and view the lidar data side−by−side with the photographs. It permits easy access to lidar data from any photograph, and conversely permits viewing the photograph associated with any lidar data.

2.4 Hyperspectral System

Table 2 outlines the design criteria for the passive hyper−spectral sensor section on EAARL which will be implemented in the last quarter of 2002. The sensor will sample the image plane of the EAARL lidar with a fiber optic which transforms a circular field stop into a linear fiber slit suitable for feeding the spectrometer. The spectrometer detector is a 46 element array of photodiode detectors which are individually connected to an array of 46 dedicated 16 bit analog to digital converters.

Table 2. Design criteria for passive hyper−spectral sensor.

Hyper−Spectral Passive section	
Field of view	3.0e−3 radians
Spatial offset from 532nm laser	3.0e−3 radians
Spectral coverage	400−860nm
Spectral channels	46
Passive digitizer	16 bits
Samples across track	120

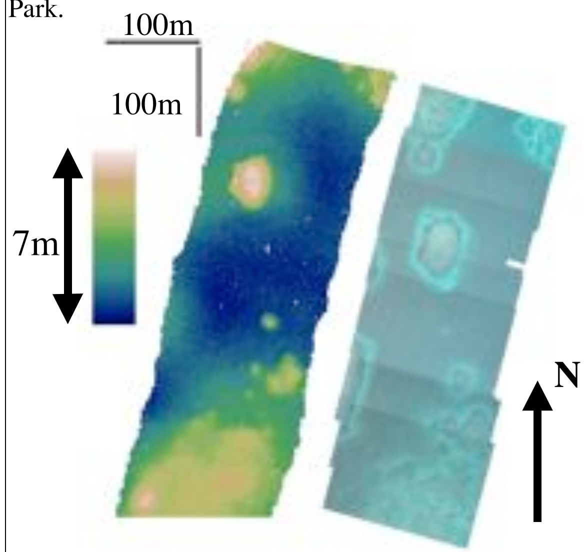
2.5 Guidance System

Course guidance data are extracted from either one of the two precision GPS receivers by a custom course guidance system developed as part of the EAARL system. The aircraft position is provided by the GPS at 10 Hertz and used to develop very high precision steering displays for the aircraft pilot. The system was designed specifically for the EAARL mission profile and minimizes the amount of interaction required by the pilot to manipulate flight lines.

2.6 Aircraft

Aircraft requirements and costs are reduced for the EAARL instrument by the sensors light weight, compact design, and low electrical power requirement. The system could be installed on a small single engine aircraft such as a Cessna 182, though NASA safety rules require the use of multi−engine aircraft over water. The surveying platform therefore is a low operational−cost privately operated light twin engine Cessna 310 aircraft. The aircraft provides good speed (180 knots) for transit to and from operating areas, and can slow to the desired 50 meters/second for survey operations. It has a maximum endurance of over 9 hours when operated at survey speed and at low altitude. It is normally single piloted during survey operations, and can operate from paved runways as short as 3000 feet in length. The system is designed to be operated by a total airborne crew of two, including one pilot, and one lidar operator/co−pilot.

Figure 3. EAARL submerged topography and digital photos showing patch reefs in Biscayne National Park.

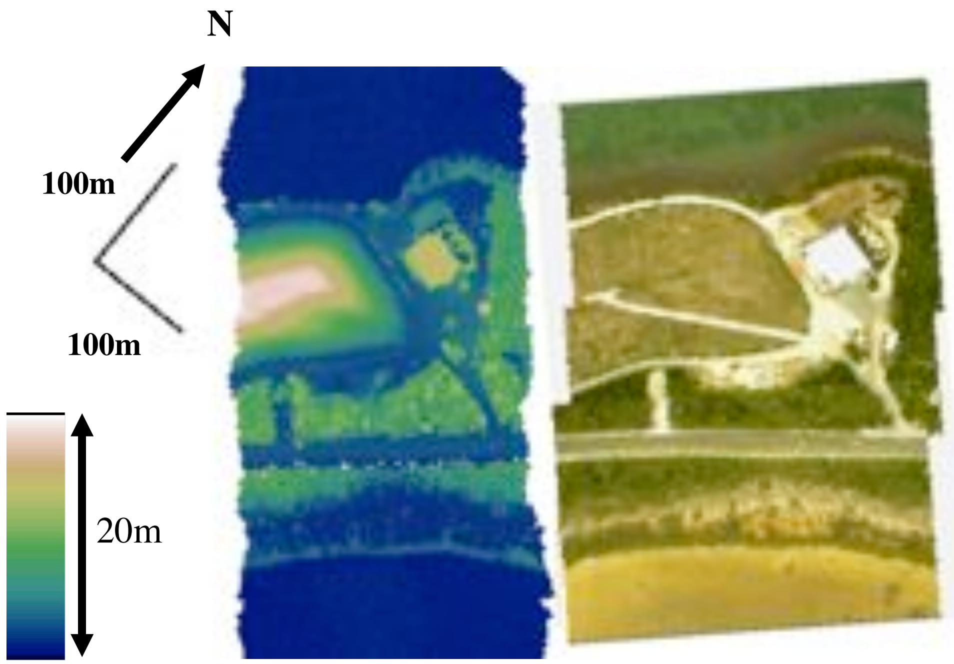


2.7 Operations

Engineering test flights of EAARL began in June of 2001. Initial test flights were conducted in the local Salisbury and Ocean City, Maryland areas over topographic and shallow submerged features in the bays separating the coastal barrier islands from the Delmarva peninsula. Flight segments were conducted to determine the various mounting bias values, and evaluate system operation and function.

Following the successful initial test flights in the vicinity of NASA Wallops Flight Facility, the EAARL system was deployed during July and August of 2001 over the Florida Keys reef tract. The Florida Keys

Figure 4.



flights extended from the Dry Tortugas across the Florida Keys National Marine Sanctuary to Biscayne National Park, and were designed to test the performance of EAARL over diverse tropical submerged and terrestrial habitats.

3. Results and discussion

Synoptic maps of coral communities based on satellite images generally portray only coarse geomorphological zones and are not sufficiently detailed or accurate to be of high value to biologists. Aircraft–based hyperspectral sensors can acquire finer scale images, but are generally quite expensive. Further, water–column contamination of the light reflected from reef benthic classes diminishes the accuracy of thematic maps derived from aircraft scanning. The EAARL is intended to mitigate these difficulties by combining a hyperspectral scanner with a laser bathymetric sounder on a light twin piston engine aircraft.

Flights based at Marathon, Florida were conducted in summer 2001 over the Florida Keys reef tract, and were designed to test the performance of the EAARL lidar over a typical Caribbean coral reef ecosystem. EAARL lidar and subsystem data were continuously acquired over numerous known reefs in transit to two regions that were swath–mapped; 1) the coral community in central Biscayne National Park, and 2) an area undergoing rapid channel sedimentation in Dry Tortugas National Park. The GPS, flight navigation, and camera and lidar systems performed within design specifications, and lidar bottom reflections were observed from water depths greater than 15 meters.

Georectified bathymetric sections have been created over patch reefs in Biscayne National Park, based on the EAARL test overflights, and corresponding digital photomosaics have been developed for these test areas (Figure 3). The altitude for the segment depicted was 210 meters yielding a swath width of 168 meters with the laser samples spaced approximately 1.4 meters apart across the flight track. The bathymetric laser data depicted herein is composed of individual laser samples and has not been filled or triangulated.

Initial processing of the EAARL test data set has also resulted in a georeferenced subaerial "first–return" elevation image and a corresponding digital photomosaic (Figure 4) depicting a landfill in the Florida Keys which was overflown during a reef mapping mission. Taken together, the bathymetric and topographic examples presented herein demonstrate the potential of using EAARL over highly variable coastal habitats within a single mission.

4.Future Work

The initial data obtained from the Florida Keys EAARL flights is being assessed and interpreted within the context of an iterative loop of (1) processing of the EAARL data to yield detailed bathymetry over selected sites, (2) comparison to ground−truth data, and (3) algorithm adjustment, followed by reprocessing of the EAARL data. The geo−positioning accuracy of the EAARL data will be assessed using an existing USGS data set. The EAARL lidar bathymetry data will be compared to detailed acoustic bathymetric measurements.

Once the accuracy of the EAARL bathymetric lidar has been verified and the EAARL hyperspectral scanner has been implemented (see Table 2), the benthic cover classification phase of the EAARL project will be initiated. Of particular interest will be an assessment of the capability to remotely map morphology and cover type within the study area. As unknown water depth fundamentally limits remote−mapping accuracy (Holden and LeDrew, 1998; Mumby et al., 1998). The EAARL compound sensor is expected to afford significant improvement. The extent of this improvement will be quantitatively assessed by processing the EAARL hyperspectral imagery with various conventional depth correction techniques, for comparison to the compound−data results. The EAARL data will also be applied to questions of change detection and event assessment. Recent results indicate, for example, that spectral discrimination can be used to distinguish coral mortality state and suggest that hyperspectral remote sensing can perhaps be used to quantitatively assess the extent of coral bleaching events (Clark et al., 2000).

5. References

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